

## **Resilient and complex infrastructure: conjugating opposite ends of the spectrum**

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### **Key words**

Infrastructure, engineering, resilience, complex systems

### **Introduction**

Over recent years there is an evolving body of Infrastructure systems, and more broadly, engineering systems', research that subscribes to the tenets of complexity science to design, optimize and improve the architecture, failure tolerance, reliability and resilience of complex engineering and infrastructure systems. A complexity perspective prompts infrastructure and engineering systems' research to reason why a system's behaviour exceeds what is intuitively the sum of its individual parts [Rouse 2007]. Although the core ideology of complexity such as adaptation, self-organization and emergence conflict with the purpose driven approach of infrastructure and engineering system design that looks for convergence of behaviours, and consistency of design and performance [Bujara 2010], still a complexity perspective has been progressively pursued, particularly for the study of system resilience, robustness and failure tolerance [Bujara 2010]. Complex systems provide the most appropriate framework for the assessment of system's reliability beyond the failure mode and effect analysis of individual systems and into the resilience of the overall system's ecosystem.

There is a compelling case on the utility of a complexity perspective in arguing resilience of large infrastructure and engineering systems, however the domain remains to be fragmented.

The reason to it is that the contemporary complex engineering research, particularly on

resilience, draws on interdisciplinary concepts borrowed from divergent fields like ecology and natural sciences and there remains some gaps in contextualising the tenets of complexity to engineering systems' research. To gain a better understanding of interdisciplinary definitions and constructs of complexity and to understand how can these be adapted in an engineering or large systems research, this study presents an interdisciplinary bibliographic synthesis of literature on complexity, resilience and engineering systems.

## **Methodology**

The bibliographic study used a co-citation mapping based analysis [Persson 2009] of the literature on complexity and resilience from last 25 years. The motivation of co-citation analysis was to be able to identify the most influential works and sectors for the research area of resilience, complexity and large engineering and infrastructure systems.

Based upon broad set of keywords, two co-citation maps were drawn; first on complexity and resilience conjugation, and second on a subset of this within engineering systems.

## **Findings**

A first co-citation analysis, indicates that the field of complexity and resilience is dominated by ecology. Other important communities are network science and environmental science. It follows that works from these areas are often cited together. Engineering and infrastructure research is a relatively small community in this scenario and the strongest connection to ecology is through the works of Hollnagel [2006] and Holling [1973]. Using a filtering criteria, based upon co-citation weights, the set of 6138 research papers listed in the basic search were reduced to a total of 325 research papers. A descriptive statistics of these articles was conducted and then individual articles were synthesised for their contribution to the domain of resilience, complexity and large systems.

A second co-citation analysis was performed on the engineering subset (Figure1). All the co-cited documents were mapped and clustered considering those co-cited more than 5 times. This highlighted the strongest reference areas for engineering research in complexity and resilience. Interestingly these include ecology and network science, whose clustering is stronger than the clustering within engineering that in comparison appears homogeneous and concentrated on resilience engineering. Here the field is dominated by the influential textbooks by Hollnagel, previously cited, Dekker, Perrow and Vaughan [Dekker 2012, Perrow 1999, Vaughan 1996]. These analyse catastrophic cascade failures and the role that the system's complexity plays in these. In particular, already in 1984 Charles Perrow [1999], framed very well the problem of ensuring safe and reliable operations of systems that become hardly predictable due to their complexity. Some of the works in the resilience engineering cluster [Saurin 2012, Costella 2009, Gomes 2009, Morel 2009, Leveson 2004, Hollnagel 2004] are often associated to the field of safety engineering. For these, the work by Woods [2006] provides the fundamental link to the cognitive aspects and the human factors in safety and resilience engineering. Some fundamental papers in network science, such as the works by Watts [1998] Barabasi [1999] and Albert [2000] are amongst the most co-cited documents in the reduced set of engineering works. It must be noted that infrastructures do not appear popular in the research area defined by the intersection of resilience and complex engineering systems.



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